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ENVIRONMENTAL POLICY AND SUSTAINABLE ECONOMIC GROWTH

AN ENDOGENOUS GROWTH PERSPECTIVE

BY

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1 INTRODUCTION

Although society's and economists' interest in environmental issues varies over time, there has always been a strong rationale for environmental policy. Externalities associated with pollution and the exploitation of natural resources (indeed the most common examples of externalities) call for intervention. It is widely believed that these externalities are large. Without an appropriate environmental policy, the environment is easily overexploited and damaged or exhausted at too fast a rate. Current production levels and economic growth rates seem to be too high to be compatible with ecologically sustainable development. Yet environmental policy turns out to be difficult to implement because of the magnitude of its expected costs. It is often tought that heavy investments and changes in technology, consumption patterns, and institutions are required and that high levels of production can no longer be maintained.

However, it is a fallacy to believe that environmental policy burdens the economy with costs too high to bear. First of all, appropriate environmental policies are required to guarantee that production (and even life) can be sustained. Natural conservation prevents doomsday. But environmental policy goes beyond assuring a minimum level of environmental quality. If indeed environmental quality is suboptimally low because of externalities, the appropriate policy that increases (investments in) environmental quality improves welfare. Instead of focusing solely on costs, often understood to refer to short-run costs in terms of production losses, we should also stress the benefits of environmental policy. In contrast to costs, the benefits arise mainly in the long run since it typically takes an extended period of time to restore damaged ecosystems and clean up polluted areas. Immaterial benefits may arise in the form of the enjoyment of a better environment that improves health and other aspects of the quality of life. However, the material benefits of environmental policy may be substantial too. Invest-

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ment in environmental quality may improve the ability of ecosystems to absorb pollution and to generate renewable productive inputs (*e.g.* through improved soil quality in agriculture). Hence, a reduction of environmental pressure in the short run may mean that pollution and the harvest from nature can be increased in the long run. Furthermore, a better environment stimulated the productivity of man-made assets. Depreciation of machinery and buildings is lower in a cleaner environment, better physical health stimulates workers' productivity and creativity, and the preservation of natural variety and biodiversity provides a source of inspiration for the invention of new medicines and materials.

This paper investigates the consequences of environmental policy for welfare, consumption and production growth in a situation in which environmental quality is initially too low. The model developed here sheds light on the nature of the costs and gains of an aggregated economic level and contrasts short-run to long-run phenomena. To acknowledge the dynamic aspects, the model is based on endogenous growth theory (notably Lucas 1988), in which the long-run growth rate of the economy depends on rational investment decisions and is affected by changes in preferences, technology and policy. When the natural environment is incorporated in endogenous growth theory, environmental policy may affect growth, both in the long run and in the short run, by affecting the productivity of investment and the savings behavior of consumers. The appropriate inclusion of the environment in growth models is based on physical science, in particular on some simple notions from the laws of thermodynamics,[1] which were advocated by Georgescu-Roegen (1971, 1975) as essential for economic theory.

The remainder of this article is organized as follows. Section 2 sorts out the basic concepts and characteristics in modeling the interaction between economic growth and environmental issues. Section 3 puts forward a one-sector model of production and environmental quality. It characterizes two types of environmental policy. Following a description of the model in sub-section 3.1, sub-section 3.2 deals with environmental policy that assures sustainable growth. Sub-section 3.3 discusses optimal environmental policy. Section 4 provides a graphical solution for the long-run growth rate and environmental quality. It shows the conditions under which environmental policy improves welfare and/or stimulates growth. Section 5 presents numerical runs of a two-sector extension of the model to illustrate the short-run consequences of exogenous environmental policy. Section 6 shows that optimal environmental policy consists of drastic reductions in pollution if environmental quality is far below its long-run optimal value, followed by increases in both pollution and environmental quality over time. Section 7 sums

1 This is one of the main features that distinguishes this paper from other papers on endogenous growth and the environment (*e.g.* Bovenberg and De Mooij 1994, Den Butter and Hofkes 1994, Gradus and Smulders 1993, Van Ewijk and Van Wijnbergen 1995, Hung *et al.* 1992, Ligthart and Van der Ploeg 1994, Verdier 1993).

up the major lessons of the article by relating them to some controversies on growth and the environment.

2 ECONOMIC GROWTH IN A FINITE NATURAL ENVIRONMENT[2]

Physical laws, especially thermodynamics laws, show that it is impossible for the physical natural environment to grow without limits. The accumulation of natural capital is bounded. First, the law of conservation of material or energy implies that no material or energy can be created in any closed system: only transformation takes place. Even worse, available material or energy is transformed into bound (or dissipated) material/energy according to the law of entropy. All energy is ultimately transformed into useless heat. Fortunately, the earth is not a closed system: high potential (so-called low entropy) solar energy enters the earth and heat leaves the earth. This inflow of solar energy can be used as a source of useful energy. It provides the energy to rearrange dispersed energy and material so that entropic processes are compensated. This fuels the formation of oxygen, the growth of forests, and (on a much larger time scale) the formation of fossil fuels. It makes the environment a renewable resource. However, since the solar energy inflow is fixed, the formation of natural resources is limited.

Economic activity has an important physical dimension: production requires transformation of physical inputs that have to be extracted from the natural environment. This is inevitably an entropic process that increases the amount of unavailable (*i.e.* dissipated or high entropy) resources at the expense of available (*i.e.* ordered or low entropy) resources: the stock of wastes increases and environmental quality decreases. Ultimately, it is unsustainable to use more natural resources than can be built up by natural processes fed by the flow of solar energy. For the same reason, an exponentially increasing use of natural resources in economic activity is unsustainable.

This is not to say that physical laws imply that economic growth[3] is impossible in the long run. The physical dimension of production (*e.g.* production measured in kilos or cubic meters of goods or by its material/energy content) does not matter in economic processes, but rather its utility value. No econmic good can be made up of physical inputs only. No utlity can be derived from a piece of metal unless we know how to use it. Hence, not only natural inputs but also knowledge are essential in the creation of economic value. If we are able to increase our knowledge, we can derive more utility from the same amount of ma-

2 The view expressed in this section is elaborated in Smulders (1995a).

3 Often, economic growth is distinguished from economic development where the former refers to quantitative increases in the scale of the economy and the latter to qualitative change. I use the term growth for both forms since it is hard to imagine economic expansion without qualitative changes (*cf.* Scott 1989).

terial inputs. Hence, knowledge creation is a necessary condition for sustainable growth.

Still, growth would be limited if knowledge creation were limited. However, no such law as the law of entropy applies to knowledge creation. According to Romer (1990), the crucial characteristic of knowledge is its non-rival nature. Once invented, an idea can be applied by many individuals many times in many places without being worn out or suffering from congestion. A law of entropy does not apply to the diffusion of knowledge. Knowledge resources are inexhaustible.

Fully in contrast to the physical law of entropy, the use of ideas does not transform and degradate ideas but is likely to add ideas. Knowledge breeds knowledge. New ideas are inspired by older ideas. The more often one and the same idea is applied by people, the more likely it yields new insights. Old knowledge creates new knowledge and knowledge creates knowledge to create knowledge (*cf.* Stiglitz 1987). Although we never know for sure (since we are by definition talking about unknown things which new knowledge is), human creativity is unlikely to be bounded.

However, the creation of new knowledge is not costless. In most instances, it requires effort and time. Invention and innovation are forms of investment, so that costs have to be incurred before benefits arise. Although the opportunity cost associated with the *use* of knowledge as an input is zero because knowledge is a non-rival input, knowledge *creation* requires rival inputs. Energy or materials should be directed to solving problems and to experimentation (or at least to feeding a man's brains). As a consequence, knowledge creation uses low entropy inputs and interferes with entropy processes.

In sum, physical laws, especially the entropy law, impose important constraints on growth and environmental preservation without excluding the possibility of sustainable economic growth. Georgescu-Roegen (1971, 1975) strongly advocated considering the implications of the entropy law in economic theory. The incorporation of the entropy law should be combined with the acknowledgement of the special role of non-rival knowledge in economic value creation. The interaction between natural limits and human creativity sets the stage for an investigation of the relationship between economic growth and environmental preservation.

3 A ONE-SECTOR MODEL OF GROWTH AND THE ENVIRONMENT

3.1 *Structure of the Model*

The model summarized in Table 1[4] is consistent with the view expressed in section 2. In particular, it acknowledges (a) that environmental processes are subject

4 Subscripts attached to function symbols refer to partial derivatives (*e.g.* $J_P = \partial J/\partial P$); a dot over a symbol denotes the time derivative (*e.g.* $\dot{N} = dN/dt$).

to the laws of thermodynamics, implying that – because of the given inflow of external (solar) energy – growth in natural resources is bounded; (b) that both knowledge and natural inputs are essential in economic production; (c) that without knowledge creation, growth runs into diminishing returns due to the laws of thermodynamics; (d) that knowledge is man-made and non-rival; (e) that knowledge creation requires investment; and (f) that knowledge creation need not be subject to diminishing returns.

Intertemporal utility, equation (1.1), depends on per capita consumption of produced goods (c) and environmental amenities. The larger environmental quality (N) is, the larger these amenities are.

The quality of the environment[5] (N) is modeled as a renewable resource, equation (1.2). Increases in environmental quality are possible through natural regeneration processes, which can be thought of as reproduction of (low entropy) resources. The services from ecosystems and solar energy inflow serve as inputs in regeneration processes. If reproduction exceeds the resources that are necessary to maintain the existing ecosystems (in the form of 'food' and other energy), the ecosystem (or environmental quality) expands. Hence, the difference between regeneration and resource use for maintenance, which is captured by $E(N)$, translates to natural growth. The law of entropy is acknowledged by the fact that regeneration processes feature diminishing returns in environmental quality (N), while the necessary resource use to maintain the existing stock of environmental resources increases more or less proportionately with environmental quality. This results in a hump-shaped relation between N and $E(N)$ (*i.e.* $E_{NN} < 0$, see Figure 1). The higher the stock of natural resources, the more difficult it is to regenerate the complete stock faster, given the fixed size of the solar inflow to earth.

Natural resources N can be used in production, but this implies transformation and hence entropy: the use (*i.e.* the entropic transformation) of natural resources in economic activity is represented by P, which decreases N. Both extraction of natural resources (where nature N acts as a source) and the disposal of wastes (where N acts as a sink) are captured by P, since both activities diminish the stock of available natural resources. The term pollution is used for short to label these activities.

Without pollution ($P = 0$), environmental quality reaches its highest possible level, the 'virgin state' $\overline{N}$, which is the maximal stock of natural resources that can be kept intact by natural regeneration. This resource stock or level of environmental quality cannot be infinite: $\overline{N}$ is bounded and constant in equilibrium, since the constant external energy inflow cannot sustain an ever growing stock of natural resources due to the laws of thermodynamics. Economic activity that transforms natural inputs by using nature as a source for resources and a sink for wastes (*i.e.*, $P > 0$) speeds up entropic processes. Then, the virgin-state stock of

5 The same symbol N is used to denote the size and productivity of the ecosystem, the stock of natural resources and the quality of the environment.

TABLE 1 – ONE-SECTOR MODEL

Preferences:	$W = \int_0^\infty U(c, N)\exp(-\vartheta t)\,dt$	(1.1)
Ecology:	$\dot{N} = E(N) - P$	(1.2)
Technology:	$J = J(K, h, N, P) = C + \dot{K} + \dot{h}$	(1.3)
Markets:	$J_P = p$	(1.4)
	$J_K = r$	(1.5)
	$\frac{\dot{c}}{c} = \left(\frac{-U_c}{U_{cc}c}\right)\left[r - \vartheta + \left(\frac{U_{cN}N}{U_c}\right)\frac{\dot{N}}{N}\right]$	(1.6)
Optimal policy:	$J_h = r$	(1.7)
	$\frac{LU_N/U_c + J_N}{J_P} + E_N + \frac{\dot{p}}{p} \equiv r^N = r$	(1.8)

natural resources can no longer be sustained, since the given energy inflow is now insufficient to compensate entropic processes. In the long run, the environment can bear a constant flow of pollution without deteriorating only if pollution matches natural growth *i.e.* if $P = E(N)$. In other words, $E(N)$ is the absorption capacity of the environment. The absorption capacity increases with environmental quality for relatively bad states of the environment, but decreases if the natural resource stock becomes large [$E_N > (<) 0$ if $N < (>) N^E$]. In the latter case, most of the natural regeneration is used in rejuvenating the environment so that only a small amount of energy is available for pollution absorption.

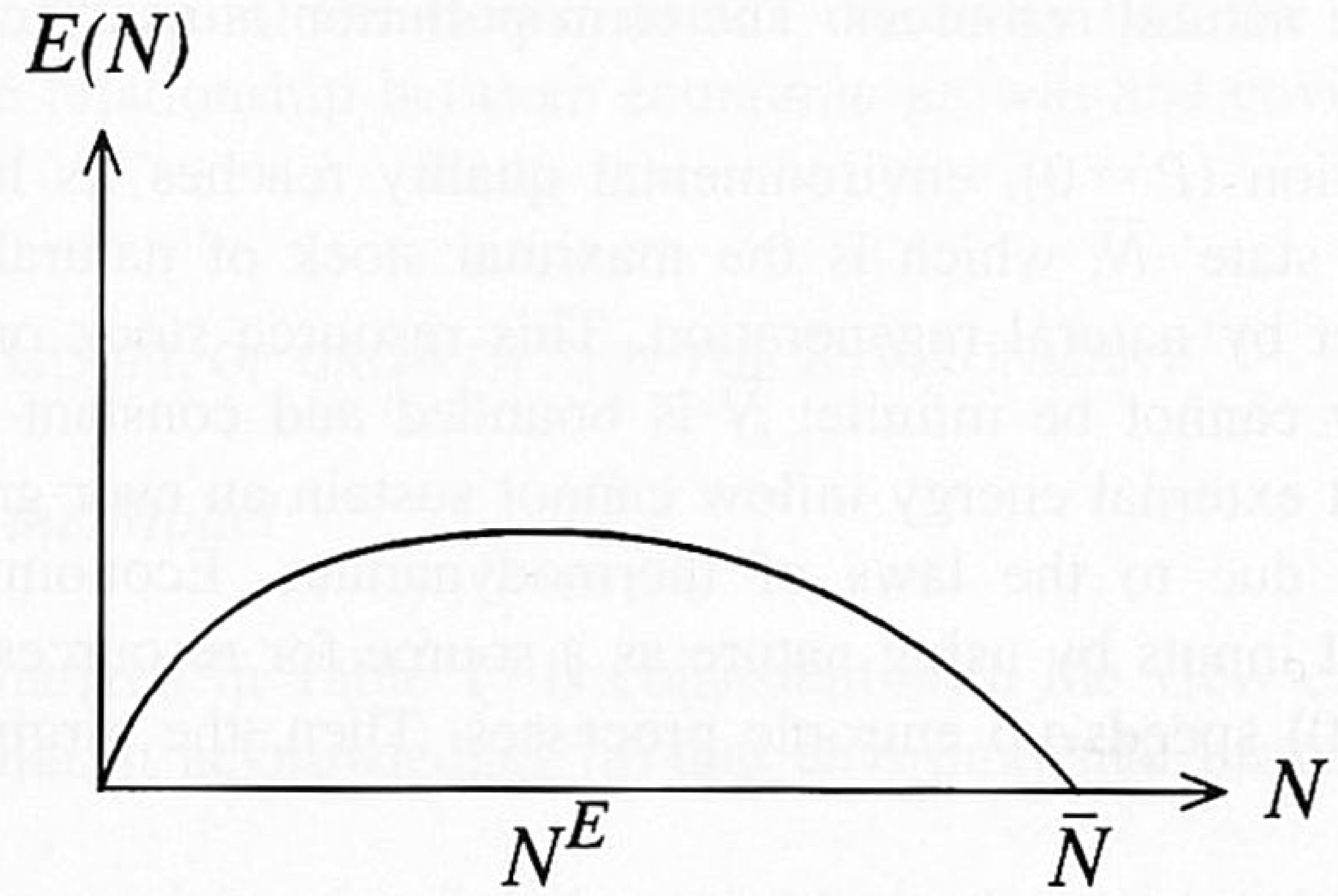


Figure 1 – The absorption capacity of the environment

Economic activity is modeled by equation (1.3). Production (J) is allocated to aggregate consumption ($C = cL$, where L is population size) and investment in new man-made inputs ($K + h$). Hence, capital formation and knowledge creation require investment. The production technology $J(\cdot)$ uses four inputs. A distinction can be made between man-made inputs and natural inputs, but also between rival and non-rival inputs. First, the man-made inputs that are rival are denoted by K. Inputs like physical capital equipment and labor (measured in efficiency units) are *rival* because a unit of these inputs that is employed by one producer cannot be employed at the same time by another producer. Second, the non-rival man-made input is knowledge, denoted by h. The inclusion of N as the third production factor reflects the fact that the higher environmental quality is, the more productive the economy is in creating useful things. If human health is better, for instance, this stimulates labor productivity and creativity. This productive aspect of nature is non-rival in use. Examples are the soil, the ozone layer and biodiversity. One and the same ozone layer protects the health of every individual on earth independent of how many individuals have to be protected. Biodiversity conserved genetic information, which inspires the search for new products and new applications of natural resources independent of how many researchers study the environment. These uses of natural resources do not deplete the resources. In contrast, the fourth production factor pollution (or energy and material use), denoted by P, depletes natural resources and is a rival natural input: the sink that is filled with pollution of one producer cannot, at the same time, be filled with the pollution of another producer.

We make the assumption of constant returns to scale with respect to man-made production factors.[6] This implies that we may rewrite $J(\cdot)$ as:

$$J(K, h, N, P) = K \cdot J(1, h/K, N, P) \equiv K \cdot \psi(h/K, N, P) \tag{1}$$

Under this assumption sustainable growth is feasible (*cf.* Rebelo 1991). Ecologically sustainable growth requires that economic variables grow, while natural variables remain constant. If resource use is constant and equal to the regeneration capacity of the environment, the environmental resource stock remains constant ($E(N) = P$, $\dot{N} = 0$). Without growth in natural inputs, growth in economic variables must be fueled by growth in man-made inputs. If K and h grow at a common constant rate, h/K is constant and the output capital ratio [$J/K = \psi(\cdot)$ in (1)] is constant, so that production grows at the same rate as man-made factors. Whether this feasible sustainable growth path is optimal depends on preferences.

6 This condition is related to substitution. Constant returns to scale in K and h require unitary elasticities of substitution between man-made inputs and natural inputs (*cf.* Dasgupta and Heal 1974, Krautkraemer 1985). An example employed in sections 5 and 6 is $J(\cdot) = A(N) \cdot F(K, Z)$, where $Z = hP$ and $F(\cdot)$ is lineair homogenous; note that the elasticities of substitution between A and F and between h and P are unity.

Whether it is actually chosen depends on the interaction between markets and environmental intervention, to which we will now turn.

3.2 *Policy to Preserve the Environment and Sustain Growth*

The second part of Table 1 summarizes the decision rules of optimizing households and firms in the market economy. Producers maximize profits by selecting the input levels of the rival producton factors, *i.e.* private capital K and pollution P. Accordingly, the marginal return on polluting inputs P equals the price p, see (1.4). This price can be interpreted either as the market price of a tradable pollution permit issued by a public environmental agency, or as the pollution charge levied by such an agency. The marginal return on capital amounts to the rate of return on capital markets, r, see (1.5).

Consumers maximize intertemporal utility by choosing a consumption path such that the return on an additional unit of postponed consumption equals the marginal utility of current consumption. This implies an extended version of the Keynes-Ramsey rule (see (1.6)). Consumers are willing to postpone consumption (*i.e.* realize growth in consumption) if the rate of return to saving is high enough (see first term in (1.6)). If produced consumption goods and the enjoyment of environmental amenities are complements ($U_{cN} > 0$), high environmental quality stimulates consumption and the prospect of improvements in the environment stimulates savings (see third term in (1.6)).

It is assumed that knowledge (h) represents generally applicable knowledge that is not only non-rival but also non-excludable: it is a public good that benefits each producer. A particular generally applicable idea can hardly be appropriated or protected by patents for example. Imitation and application in many production processes follows.[7] There cannot be competitive markets for non-rival, non-excludable goods. No individual agent willingly pays for a good he can benefit from freely. If knowledge is not priced, no private incentive exists for (intended) accumulation of new knowledge.

If public provision of new knowledge also fails, diminishing returns with respect to rival capital inputs will decrease the rate of return in a growing economy in which resource use is constant. Given a constant input level of natural inputs (N and P) and a constant stock of general knowledge h, the marginal return on private capital K falls when it is accumulated ($J_{KK} < 0$). The fall in the interest rate decreases savings (see (1.6)) and the incentive for growth diminishes. A public agency should subsidize knowledge creation in order to sustain growth. The

7 This rather extreme assumption of complete non-excludability of knowledge has the advantage that the assumption of perfect competition can be maintained. Alternatively, if knowledge is (partly) excludable (*e.g.* by means of patents) or if knowledge is (partly) firm-specific, *private* firms will have an incentive to invest in own environmentally friendly technologies. However, firms will then have market power. Still, knowledge remains a kind of public good as long as knowledge spillovers are present, so that private knowledge creation is suboptimal, calling for government intervention.

diffusion of new knowledge then compensates the diminishing returns with respect to rival capital accumulation. If public policy assures that the creation of general knowledge keeps pace with the accumulation of private capital, then the rate of return r remains constant over time. If the long-run rate of return exceeds the pure rate of time preference and if the elasticity of intertemporal substitution is independent of the scale of consumption (*i.e.* $-U_c/U_{cc}c$ equals a constant, say σ_c), consumption grows at a constant positive rate.

Furthermore, the second task for public policy in sustaining growth is to assure a stable and sustainable pollution level. If a constant knowledge capital ratio h/K is maintained, growth in man-made assets increases the marginal productivity of natural rival inputs (see (1): $J_P = K \cdot \psi_P$). This requires a pollution charge that rises at the same rate as man-made inputs grow (*i.e.* $\dot{p}/p = \dot{K}/K = \dot{h}/h$) in order to assure constant pollution levels in the long run. Alternatively, a public agency should auction off a *fixed* number of tradable pollution permits. Market forces will drive up the price of the permits (p). The natural growth function constrains the long-run level of physical pollution. To preserve environmental quality, the extraction of natural resources should be compensated by natural growth: $P = E(N)$. Hence the maximum long-run pollution level equals the maximum absorption capacity (*viz.* $E(N^E)$, see Figure 1).

If the government assures a steady h/K ratio and a stable pollution level P that equals the long-run absorption capacity of the environment, a steady state exists that is characterized by:

$$\dot{K}/K = \dot{h}/h = \dot{J}/J = \dot{c}/c = \dot{p}/p = g, \qquad \dot{N} = \dot{r} = \dot{g} = 0. \tag{2}$$

where we abstract from population growth ($\dot{L} = 0$, so that $\dot{C}/C = \dot{c}/c$).

3.3 *Optimal Environmental Policy and Growth*

By maximizing (1.1) subject to (1.2) and (1.3), one finds the optimal allocation. The present value Hamiltonian and the associated optimality conditions read:

$$\mathcal{H} = e^{-\vartheta t}\{U(c,N) + \mu[J(K,h,N,P) - cL] + \nu[E(N) - P] + \lambda[K + h - M]\}$$

$$U_c = \mu L \tag{3}$$

$$J_P = \nu/\mu \tag{4}$$

$$J_h = J_K \tag{5}$$

$$\mu J_K = \vartheta\mu - \dot{\mu} \tag{6}$$

$$U_N + \mu J_N + \nu E_N = \vartheta\nu - \dot{\nu} \tag{7}$$

Differentiate (3) with respect to time, substitute the result in (6), and denote the marginal product of capital by r (see (1.5)) to find the Ramsey rule (1.6).

Equation (4) reveals that the marginal product of pollution, which equals the pollution price p in the market equilibrium (see (1.4)), should equal the ratio of the shadow price of environmental quality divided by the shadow price of production. In other words, the marginal benefit of pollution arising from additional production (J_P, which is valued μ) should equal the marginal cost of pollution, which arises because additional pollution decreases environmental quality (which has shadow price ν).

Equation (5) states that the marginal product of private capital, which equals the interest rate r in the market equilibrium (see (1.5)), should equal the marginal product of knowledge. This implies that the knowledge capital ratio h/K is set in such a way that it maximizes output per unit of man-made capital ($M \equiv K + h$), given P and N. Due to the assumption of constant returns to scale, it also implies that the marginal product of capital, and thus the rate of interest, equals the average productivity of man-made assets[8]

$$r = J_K = J/M \tag{8}$$

where M denotes total man-made assets, $M \equiv K + h$.

Equation (7) determines the shadow rate of return of the environment, denoted by r^N. Differentiating (4) with respect to time and combining the result with (3), (4), (6), (7), (1.4), and (1.5) yields equation (1.8). This optimum condition is a generalization of the Hotelling rule, which guarantees that the exploitation of the environment as a natural capital stock yields a return (r^N, on the LHS of (1.8)) that equals the return on alternative capital goods (r, on the RHS). If the environment were a non-renewable resource without amenity value and without capacity to provide non-rival services to production (*i.e.* if the first and second term were zero), the price of extracted resources should grow at a rate that equals the rate of interest. The loss of future revenue from exploiting the environment due to depletion should be compensated by increases in the price of the resource. In other words, the rate of return on exploiting the environment consists of capital gains only, which should equal the return on alternative forms of capital. The second term in (1.8) indicates that the price of a renewable resource has to rise at a faster rate than r as long as $E_N < 0$. The reason is that extracting use of the environment not only depletes (the per period growth of) the resource but also decreases the future capacity to regenerate. This decreases the revenue from the exploitation of the environment, which should be compensated by additional price increases to realize a sufficiently high return. The first term on the LHS in (1.8) indicates the return derived from environmental capital stemming from the ame-

8 From (1) we find $J_K = \psi - (h/K) \cdot \partial\psi/\partial(h/K)$ and $J_h = \partial\psi/\partial(h/K)$. Substitute this in (5) to find $\partial\psi/\partial(h/K) = \psi \cdot K/(K + h)$. Note that $\partial\psi/\partial(h/K) = J_h = J_K$ and that $\psi = J/K$, bringing us to (8).

nity value and productive services from the environment. Alternatively, $\dot{p}/p$ can be interpreted as the rate at which natural inputs become scarcer over time, *i.e.*, the rate at which nature is depleted. This rate is lower the larger the first term is, for a given required rate of return r. The more important non-rival productivity and amenity services from environmental quality are, relative to the productivity of natural resource extraction, the lower is the incentive to deplete the resource.

Equation (1.8) reveals the condition on preferences under which a balanced growth path, as characterized in (2), is optimal. If pollution and environmental quality are constant and man-made assets grow at a common rate g, the marginal productivity of pollution J_P and hence its price p, and the marginal product of environmental quality J_N grow at the same rate g (see (1)). The term E_N and the rate of return $r = J_K$ are constant. This balanced growth path can only be consistent with the optimality condition (1.8) if U_N/U_c also grows at rate g over time. This requires that preferences feature sufficient substitution between produced consumption and environmental amenities. If the elasticity of substitution were less than unity, the importance of amenities in utility would increase as long as consumption grew faster than environmental quality. Then, it would be optimal to sacrifice an ever larger part of production to improve environmental quality in line with growing consumption of produced goods. Since environmental quality cannot be increased beyond the virgin state, the long-run equilibrium is then a stationary steady state without growth in either consumption or environmental quality. In contrast, with a larger elasticity of substitution, growing consumption substitutes for environmental amenities. In the sequel we assume that balanced growth is optimal by assuming a Cobb-Douglas instantaneous utility function $U(c, N)$ characterized by a constant weight of amenities relative to produced consumption $U_N N/U_c c \equiv \phi$.[9]

4 WELFARE GAINS AND LONG-RUN GROWTH EFFECTS OF ENVIRONMENTAL POLICY

4.1 *Costs and Benefits of Environmental Policy*

The welfare gains of investment in environmental quality can be illustrated by the steady-state version of the Hotelling rule (1.8) which can be rewritten as (use (2) and $C = cL$):

$$\frac{P}{N}\left[\phi\frac{C}{J}+a\right]\left(\frac{1}{r-g}\right)+\frac{\omega E_N}{r-g}-\omega=0 \tag{9}$$

9 If the elasticity of substitution is larger than one, the weight of amenities in utility ($U_N N/U_c c$) declines as long as the economy grows. In the long run this weight then approximates zero and the associated optimum chan be characterized by setting ϕ equal to zero.

where

$$\phi \equiv U_N N/U_c c, \quad a \equiv J_N N/J \quad \text{and} \quad \omega \equiv J_P P/J.$$

The LHS in (9) represents the net benefits from a small change in environmental quality along a balanced growth path. In particular, starting from a balanced growth path where pollution equals the absorption capacity ($P = E(N)$), decreasing pollution today by $\mathrm{d}P$ increases tomorrow's environmental quality by $\mathrm{d}N = -\mathrm{d}P$. To maintain this increase, tomorrow's pollution level should be adjusted to the new absorption capacity, which has risen by $-E_N\,\mathrm{d}P$.[10] If this small change in pollution has no effect on welfare, the initial path was optimal.

The third term on the LHS of (9) represents the costs associated with a reduction in pollution. A decrease in pollution requires lower input levels of polluting inputs, which decreases production per unit of man-made capital: a one percent decrease in polluting inputs decreases production by ω percent. The second term represents the direct future consequences of higher environmental quality. If $E_N > 0$, absorption capacity improves to that long-run pollution and rival natural input levels increase (by E_N percent), which yields productivity gains (ωE_N percent) in each future period, to be discounted by $r - g$. If $E_N < 0$, absorption capacity declines and the investment in the environment has a cost in the form of permanent lower levels of polluting inputs.

The first term on the LHS of (9) represents the direct benefits derived from higher future environmental quality, discounted by $r - g$. A one percent decrease in pollution increases environmental quality by P/N percent in the long run. Higher environmental quality increases productivity of man-made capital goods (a percent per percent of environmental improvement). Moreover, it stimulates environmental amenities, which can compensate for the loss in productivity. In particular, the larger the weight of amenities in utility is relative to consumption (ϕ), and the larger the share of consumption in production (C/J), the larger are the benefits of increased amenities relative to production losses.

In an optimum, marginal costs are equal to marginal benefits. Hence, (9) is satisfied on a balanced optimal-growth path.

4.2 *Environmental Policy when Environmental Quality is too Low*

A discussion about changes in environmental policy is most interesting if it is applied to a situation in which environmental quality is too low. The incentive to change environmental policy is then to internalize more fully the benefits from

10 In terms of percentage changes, from tomorrow onwards a P/N percent higher environmental quality can be maintained if pollution today is 1 percent lower than initially and pollution tomorrow is E_N percent higher. (Note that $\mathrm{d}N/N = (P/N) \cdot (\mathrm{d}P/P)$ and that $\mathrm{d}E(N)/E(N) = E_N \cdot \mathrm{d}N/E(N) = E_N \cdot (\mathrm{d}N/N) \cdot (N/P)$ since $E(N) = P$).

investment in the environment. To study such a situation, consider te model in Table 1, where the equality sign in (1.8) is replaced by the greater-than sign: the returns on environmental investment exceed the return on alternative investment ($r^N > r$) and the net benefits of environmental investment (on the LHS in (9)) are positive. If public policy implements a shift towards environmental investment, welfare will improve. This section concentrates on the steady-state effects of environmental policy, while the next two sections deal with the transitional impacts.

The long-run (or steady-state) growth rate follows from (1.6) and (1):

$$g = \sigma_c(r - \vartheta) \tag{10}$$

where $\sigma \equiv -U_c/U_{cc}c$ represents the elasticity of intertemporal substitution. Growth depends positively on the rate of return to investment in man-made assets, which is given in (8). Substitute the optimal knowledge-capital ratio which is implicitly determined by (5) in (1), and write this return as a function of P and N only. The long-run pollution level is determined by absorption capacity $E(N)$. Hence, write the long-run mate of return on man-made assets as:

$$r = \rho(E(N), N) \tag{11}$$

The hump-shaped curve in Figure 2 depicts equation (11). The rate of return to capital is zero when absorption capacity is zero, *i.e.* when $N = 0$ or $N = \bar{N}$, for no polluting inputs, which are necessary for production, can then be used. Increases in environmental quality boost the rate of return as long as the absorption capacity is increasing ($E_N > 0$ if $N < N^E$), since production benefits both from higher sustainable flows of polluting inpus (first argument in (11)) and from higher non-rival productive services from the environment (second argument). However, for higher levels of N, the absorption capacity declines so that there is a trade-off between environmental quality and long-run pollution ($E_N < 0$ if $N > N^E$): polluting human activities and entropic natural regeneration processes are at such a high level that the former crowds out the latter in the competition for solar energy. Even then the rate of return increases if the effects of higher non-rival productive services associated with improved environmental quality dominate the fall in productivity due to lower polluting-input levels. If both effects cancel each other out, the long-run rate of return on man-made capital is maximal. Take into account (5)[11]:

$$\frac{\mathrm{d}r}{\mathrm{d}N} \gtreqless 0 \;\Leftrightarrow\; \omega\left(\frac{E_N N}{P}\right) + a \gtreqless 0 \tag{12}$$

11 From $r = J/M$ and $P = E(N)$ we find $\mathrm{d}r/\mathrm{d}N = (1/M) \cdot [J_N + J_P \cdot E_N + J_K \cdot \mathrm{d}K/\mathrm{d}N + J_h \cdot \mathrm{d}h/\mathrm{d}N] - (J/M^2) \cdot \mathrm{d}M/\mathrm{d}N$. Substituting $J_K = J_h$ and $\mathrm{d}M = \mathrm{d}K + \mathrm{d}h$, setting the result equal to zero, and substituting the definitions of ω and a, we find (12).

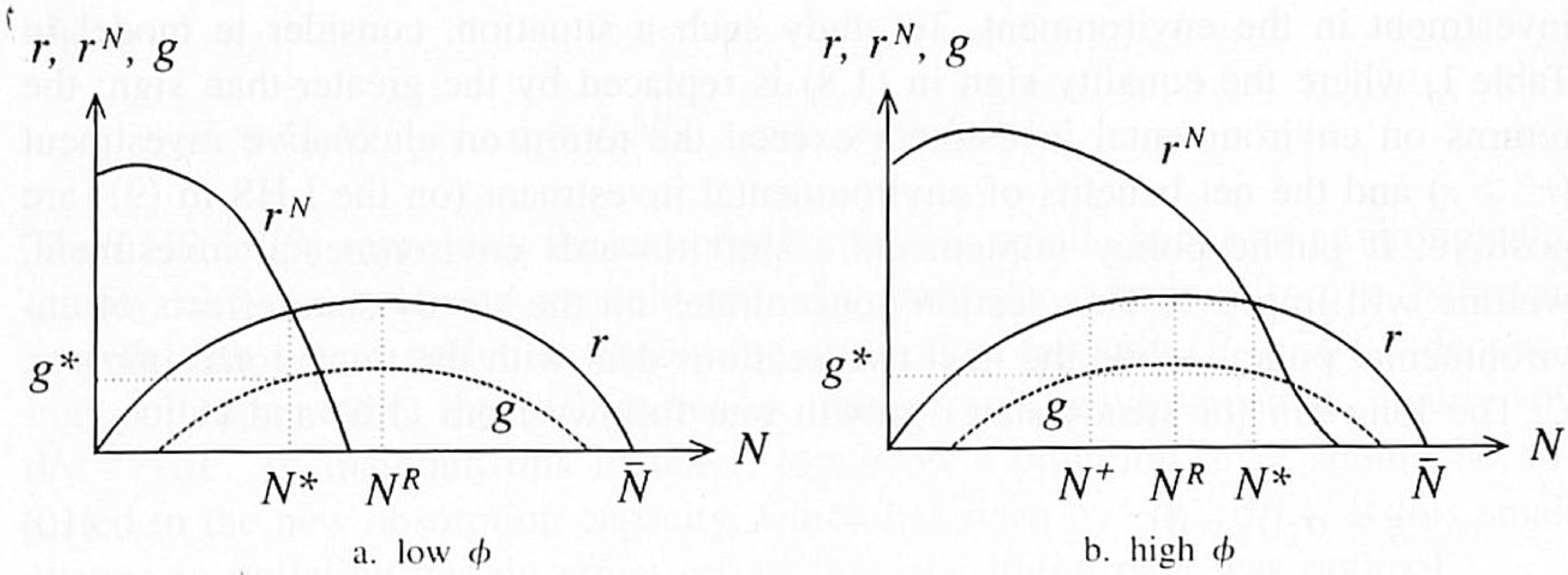


Figure 2 – Long-run equilibrium

Condition (12) with equality sign gives the maximal rate of return r; the associated level of environmental quality is denoted by N^R, which exceeds N^E (*i.e.* the level for which absorption capacity is maximal, see Figure 1) as long as $a > 0$.

Substituting (11) into (10), now draw the long-run growth rate as a function of the long-run level of environmental quality (see Figure 2). Obviously, increases in the long-run rate of return stimulate long-run growth. Hence, the sign of the LHSs in (12) equals the sign of dg/dN. If we start at such a low level of environmental quality that the LHSs in (12) are positive (*i.e.*, if $N < N^R$), growth is stimulated by investment in the environment. This yields the important conclusion that environmental policy always stimulates growth if the environment is initially badly damaged. A badly damaged environment implies that there is room for improvement in absorption capacity ($E_N > 0$) so that in the long run the economy can harvest more resources from the environment and pollute more without deteriorating environmental quality. Moreover, higher environmental quality implies higher non-rival productive services ($a > 0$). Both facts improve the productivity of the economy in the long run.

To simultaneously show the welfare consequences, the long-run rate of return on man-made capital r is confronted with the long-run return to environmental investment r^N. The latter follows from the Hotelling rule in (1.8), the balanced growth characterization in (2), and the definitions of ϕ, ω, and a in (9):

$$r^N = g + E_N + \frac{E(N)}{N}\left(\frac{1}{\omega}\right)\left(a + \phi\frac{C}{J}\right) \tag{13}$$

Figure 2 depicts r^N as a function of N, which follows after substitution of $C/J = (r - g)/r$,[12] (10), and (11) into (13).

The rate of return to environmental quality falls with the stock of environmental capital ($dr^N/dN < 0$) in most situations. This can be seen by examining how

12 From $J = C + M$, see (1.3), $\dot{M}/M = g$, see (2), and $\dot{J}/M = r$, see (8), we find $C/J = (r - g)/r$.

the separate terms in (13) depend on N. The assumption that marginal natural growth is diminishing when natural quality expands, *i.e.* $E_{NN} < 0$, which was derived from the entropy law, implies that the steady-state pollution to environmental quality ratio, $P/N = E(N)/N$, and the marginal absorption capacity E_N are decreasing in N (see Figure 1). Under plausible assumptions, the production elasticity of environmental quality (a) is non-increasing in N. If the elasticity of substitution between rival man-made and natural inputs is less than unity (*i.e.* if rival natural inputs P are essential), the production elasticity of polluting inputs (ω) increases if these inputs become scarcer due to a decline in the absorption capacity. Hence, $1/\omega$ is decreasing in N for $N > N^E$. However, owing to general equilibrium feedback mechanisms, non-concavities may arise. Increases in N may increase $1/\omega$ (if $N < N^E$), increase g (if $N < N^R$) or increase $C/J = (r - g)/r$ (if $N > N^R$). For low N, investment in the environment increases absorption capacity, sustainable pollution (see Figure 1), the rate of return on man-made assets (see (11) and (12)) and productivity growth (see (10)), which tends to increase r^N. For high N, the rate of return on man-made assets declines, which stimulates consumption of both produced goods and environmental amenities (C/J) so that r^N tends to rise. These tendencies explain the 'lumps' in the shape of the r^N-curve.

Where the rate of return on natural capital exceeds the rate of return on man-made assets, *i.e.*, where the r^N-curve lies above the r-curve in Figure 2, it pays to invest more in environmental quality. Hence, where the r^N-curve cuts the r-curve from above, environmental quality is optimal.[13] The corresponding growth rate, to be read from the broken g-curve, is the optimal growth rate. The figure illustrates the long-run consequences of environmental policy. The interesting case is the one in which the economy starts with too low environmental quality. Hence, the initial balanced growth equilibrium of the experiments is represented by a point on the r-curve that is situated to the left of the point of intersection with the r^N-curve. The consequences of *small* changes in environmental quality on the growth rate depend on the slope of the broken g-curve, measured at the relevant level of N. The sign of this slope is the same as the slope of the r-curve and is determined by (12). Small changes are explored in the next sections by applying a linearized version of the model. However, *large* changes in environmental policy, *e.g.* from a sub-optimal situation towards the optimum, require a global analysis, for which Figure 2 is useful. Insight can be enhanced by considering two special cases before turning to the general implications of Figure 2.

13 It can be shown that such a point of intersection is a saddle-point stable equilibrium (*cf.* section 6). If r^N intersects r from below, the point of intersection is an unstable equilibrium. For the sake of brevity, we assume existence, stability and uniqueness of the equilibrium in this article. However, due to the on-convexities that are explained above, there may be multiple equilibria so that the initial starting point determines the long-run equilibrium (hysteresis). In particular, an economy that neglected environmental quality for along time, may be trapped in a low-quality equilibrium. See Smulders (1995) for further details.

First, consider the case in which the environment is purely a sink for wastes and a source of resources, while no non-rival services in production or utility are provided (*i.e.* $a = \phi = 0$). This case is well-known from the literature on renewable resources (see *e.g.* Dasgupta 1982). The optimum stock of natural resources results if the marginal returns on the environmental equal the discount rate: $E_N = r - g$ (>0) (see (9)). This implies that the rate of return r is below its maximum because absorption capacity and hence long-run resource extraction P are below their maximum. Since future benefits are discounted, it is optimal to give up some of the long-run benefits associated with the maximal absorption capacity in order to reap short-run benefits associated with temporarily higher pollution, which decreases future absorption capacity. If environmental quality is initially too low ($E_N > r - g$ so that $r^N > r$), the present value of future benefits of investing in the environment exceeds the cost. Starting from such an initial balanced growth path, environmental policy that boosts environmental quality also boosts the absorption capacity, long-run sustainable pollution levels, and the productivity of man-made assets. Hence, environmental policy stimulates growth if the environment is a pure natural resource.

Next, consider the case in which the environment also provides non-rival services in production (*i.e.* $a > 0$ but $\phi = 0$). In this case, the natural environment acts as a public capital good. Environmental quality is optimal if $r^N = r$, which implies (see (13)):

$$\omega\left(\frac{E_N N}{E}\right) + \left(\frac{-E_N}{r - g - E_N}\right) a = 0 \tag{14}$$

Comparing (12) to (14), note that $dr/dN > 0$ if (14) is satisfied (note that the second term in brackets in (14), which is absent in (12), is less than one). Hence, the rate of return is not maximized in the optimum. The reason is again that the benefits of environmental improvement come only in the long run, while costs occur immediately and the future is discounted. However, the optimal level of environmental quality is higher than in the absence of non-rival productive services. Starting from too low environmental quality, environmental policy improves both environmental quality and growth.

Now consider the general case in which the environment is both a public capital good and a public consumption good (*i.e.* $a > 0$ and $\phi > 0$), see Figure 2. The optimal level of environmental quality is determined by the intersection of the r-curve and the r^N-curve. If the amenity value of te environment is high (*i.e.* if ϕ is high), it is optimal to choose a high level of environmental quality (N^*). Consequently, optimal absorption capacity and sustainable pollution may be rather low ($E_N < 0$), which results in a rather low rate of return (the r^N-curve cuts the r-curve to the right of its top: $N^* > N^R$). This case shows a trade-off between produced consumption goods and natural consumption goods (*i.e.* amenities).

Since the weight of amenities is relatively high (as indicated by a high value of ϕ), it is optimal to sacrifice absorption capacity and productivity in order to enjoy high amenities. If environmental quality is not far below this optimum, the optimal environmental policy will hurt long-run growth. However, if the economy starts at a very low level of environmental quality, full internalization of all benefits of the environment may increase the long-run growth rate. In Figure 2, the latter is the case if initial environmental quality is below N^+ (where N^+ denotes the lower level of N for which the rate of return r is the same as in the optimum: $\rho(E(N^+), N^+) = \rho(E(N^*), N^*)$.

4.3 *A Shift in Preferences Towards the Environment*

Finally, consider a situation in which preferences shift slightly towards the environment, away from produced consumption goods, *i.e.* ϕ increases slightly, starting from an optimum. This shifts the r^N-curve upwards. The optimal steady-state level of environmental quality increases. Growth increases if initially the r^N-curve intersects the r-curve to the left of the top of the r-curve. This is the case if (combine (12) and (13)):

$$ar + E_N \phi > 0 \tag{15}$$

An increase in ϕ triggers an increase in demand for environmental quality. Moreover, it makes the environment more important as a consumption good relative to its role as a capital and resource good. The role as a capital good is indicated by the first term in (15): the larger the production elasticity a is, the more productive the stock of natural capital will be in production; the higher the rate of return r is, the more important investment will be relative to consumption. The role of the environment as a sink and a source is indicated by E_N: if E_N is positive, the environment is productive at the margin in providing resources and absorbing pollution. If ar and E_N are large relative to ϕ, the environment is a productive good and investing in it increases productivity and growth. However, if ϕ is relatively large and E_N is negative (*i.e.* increasing N decreases its capacity to absorb pollution and provide resources), the environment is a consumption good. Increasing environmental quality then crowds out investment and hurts growth.

5 THE DYNAMICS OF EXOGENOUS ENVIRONMENTAL POLICY

The long-run consequences of environmental policy, as discussed above, differ from the short-run consequences, since it takes time to adjust the stocks of environmental and man-made capital. To study the short-run and medium-run consequences, the dynamic model in Table 1 is disaggregated into a two-sector version (which parallels Bovenberg and Smulders (1993, 1994)) and linearized around a balanced-growth path. This section presents numerical runs for different parameterizations.

5.1 *A Two-sector Extension*

Table 2 shows the two-sector version. The specification of the instantaneous utility function in (2.2) allows for optimality of balanced growth. Total man-made production J is disaggregated into two sectors. First, the Y-sector produces final consumption goods (C) and private capital goods (K), see (2.3). Second, the H-sector creates public non-rival knowledge, see (2.4). This disaggregation allows for differences in technology. In particular, we assume that knowledge production uses man-made inputs more intensively, while final goods and private capital production are relatively pollution-intensive. Also, the disaggregation makes it possible to distinguish the publicly financed environmental H-sector from the private Y-sector.

Public knowledge is interpreted as 'environmentally friendly' technology; *i.e.* the stock of knowledge h determines the productivity of rival natural inputs P so that natural inputs are measured in efficiency units $Z = hP$. The production functions of both sectors are specified according to (2.3) and (2.4). Technology in both sectors exhibits constant returns with respect to private capital K and effective pollution Z, and the elasticity of substitution between these inputs (σ_{KZ}) is less than unity to stress the essentiality of natural outputs. Environmental quality affects total factor productivity in both sectors (A_Y and A_H, respectively).

Sectoral allocation is determined by (2.7) and (2.8). Arbitrage in the capital and pollution-permit markets ensures that capital and pollution earn the same return in both sectors. Here q is the price (subsidy) paid for new environmentally friendly technologies (*i.e.* the price of output from the H-sector). Equations (2.9)-(2.11) are the specificatons of (1.4)-(1.6). Equation (2.12) is the counterpart of (1.7).

The government decides on the number of pollution permits. This section assumes that this number is set suboptimally at a level that implies too low a level of environmental quality. Hence, the shadow rate of return to environmental investment exceeds the rate of return on man-made capital (see (2.13), the counterpart of (1.9)).

A public agency auctions off the fixed number of pollution permits to polluting firms and uses the revenues to finance research and development in environmentally friendly technical knowledge. Hence, polluters (firms) pay, although in an indirect way. The objective of the agency is to maximize net cash-flows. It takes the number of pollution permits, which is determined by the government, as given. The single instrument of the agency is the price of knowledge, q, which can be interpreted as the subsidy the agency grants for the development of envi-

TABLE 2 – TWO-SECTOR MODEL

Preferences:	$W = \int_0^{\infty} \frac{(c \cdot N)^{1-1/\sigma_c}}{1-1/\sigma_c} \exp(-\vartheta t)\, dt$	(2.1)
Ecology:	$\dot{N} = E(N) - P$	(2.2)
Technology:	$Y = A_Y(N) \cdot F(K_Y, Z_Y) = C + \dot{K}$	(2.3)
	$H = A_H(N) \cdot G(K_H, Z_H) = \dot{h}$	(2.4)
	$K_Y + K_H = K$	(2.5)
	$Z_Y + Z_H = hP$	(2.6)
Markets:	$A_Y\, (\partial F/\partial K_Y) = qA_H\, (\partial G/\partial K_H)$	(2.7)
	$A_Y\, (\partial F/\partial Z_Y) = qA_H\, (\partial G/\partial Z_H)$	(2.8)
	$A_Y\, (\partial F/\partial Z_Y)h = p$	(2.9)
	$A_Y\, (\partial F/\partial K_Y) = r$	(2.10)
	$\dot{c}/c = -\phi\dot{N}/N + \sigma_c(r + \phi\dot{N}/N - \vartheta)$	(2.11)
Public policy:	$A_H\, (\partial G/\partial Z_H)P + \dot{q}/q = r$	(2.12)
	$\left[\frac{LU_N}{U_c} + \left(\frac{\partial A_Y}{\partial N}F + q\frac{\partial A_H}{\partial N}\right)\right]\frac{1}{p} + E_N + \frac{\dot{p}}{p} \equiv r^N = r$	(2.13)

ronmentally friendly technologies. The optimal subsidy assures that the return on knowledge equals the return on private capital (*cf.* (5) and (1.7)).[14]

All results derived in section 3 carry over the steady state of the two-sector version if the appropriate aggregation procedures are applied and if economy-wide elasticities are defined as weighted averages of sectoral elasticities.[15]

14 In the one-sector model, the optimal relative price of knowledge is unity and $\dot{q}_h = 0$ because there is only one production technique. Then, in each period the agency chooses the 'purchases' of new technology. In the two-sector version, the *H*-sector provides the optimal amount of R&D if the agency chooses the right price.

15 The production elasticity of non-rival environmental services a and the production elasticity of pollution ω are defined as:

$$a = \left(\frac{Y}{q_J J}\right)\frac{\partial A_Y}{\partial N}\frac{N}{A_Y} + \left(\frac{qH}{q_J J}\right) \text{ and } \omega = \left(\frac{Y}{q_J J}\right)\frac{Y_P P}{Y} + \frac{\partial A_H}{\partial N}\frac{N}{A_H}\left(\frac{qH}{q_J J}\right)\frac{H_P P}{H}$$

where q_J is the price index of aggregate production. Producton and man-made assets are aggregated as $q_J J = Y + qH$ and $q_M M = K + qh$ (note that in the one-sector model $q_J = q_M = q = 1$).

5.2 *Solving the Two-sector Model*

By linearizing equations (2.1)-(2.12) around a balanced growth path, Bovenberg and Smulders (1994) found analytical expressions for the consequences of a small permanent reduction in pollution. These consequences depend on the initial balanced growth path. In particular, the consequences for growth depend on, among others things, whether environmental quality acts mainly as a public consumption good (ϕ is large) or as a public capital good (a is large).[16] The consequences for welfare depend on the difference between the rate of return on man-made assets and that on environmental quality. The following sub-sections show the consequences of pollution reduction. In each scenario, a permanent ten percent pollution reduction from time $t = 0$ onward disturbs the initial growth path. It is assumed that initially $E_N < 0$, so that this policy leads to a new stable equilibrium with higher environmental quality. The only exception is scenario 5, where $E_N > 0$ and the exogenous change in pollution takes the form of a once-and-for-all reduction in the pollution ratio P/N, which also yields a stable equilibrium. The scenarios differ with respect to the initial steady state, as indicated by differences across scenarios in the initial values for σ_c, ω, σ_{KZ}, ϕ, a, and E_N. The numerical results for variables marked by a tilde ($\tilde{}$) in the tables and figures are percentage deviations from the initial steady state.

5.3 *Benchmark Scenario*

The first scenario illustrates a situation in which a tighter environmental policy exerts adverse effects on production and growth in the short run, but moderate positive effects in the long run. Figure 3 shows the time path for the main variables in scenario 1.

In the short run, the reduction in pollution implies a lower level of polluting inputs in production activities, which hurts the productivity of man-made assets. Hence, the additional investment in environmental quality crowds out physical production and hurts the rate of return on man-made assets. Furthermore, pollution reduction requires a relocation of economic activity from the pollution-intensive private sector towards the publicly subsidized environmental R&D sector. The reduction in pollution enhances future environmental quality. As a consequence, consumers expect a double future benefit: not only a higher amenity value of the environment, but also a higher productivity of accumulated assets, which raises permanent income. Initial consumption rises as consumers anticipate these gains. In the short run, not only the level of production, but also the growth rate of production fall. The decline in the rate of return and the increase in consumption levels decrease investment in man-made assets.

16 To be precise, long-run growth rises (falls) if the LHS in (12) is positive (negative). This is more likely if environmental quality is lower than optimal and ϕ is small (large).

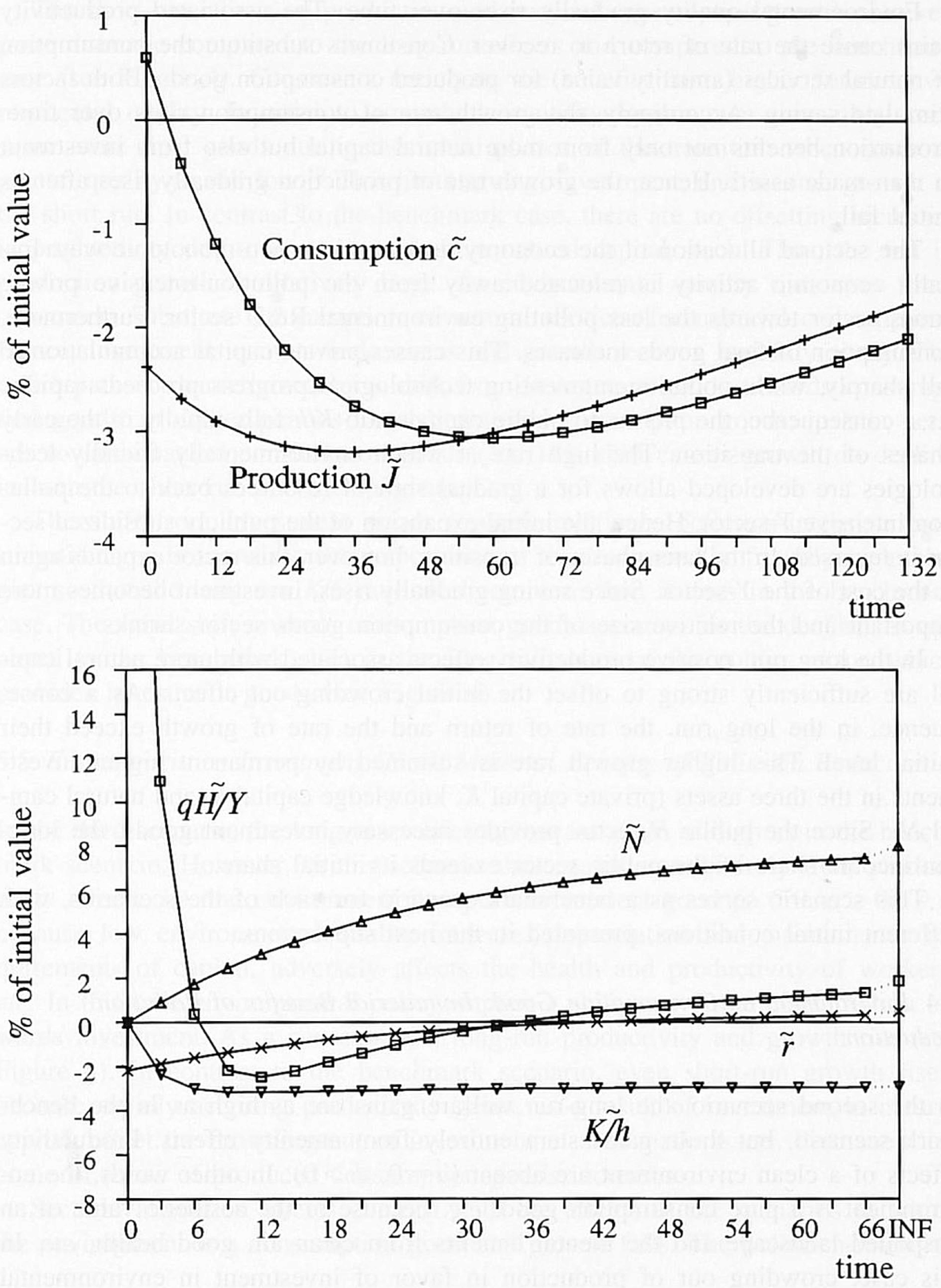


Figure 3 – Benchmark scenario.
Parameter choice: see Table 3, column 1

Environmental quality gradually rises over time. The associated productivity gains cause the rate of return to recover. Consumers substitute the consumption of natural services (amenity value) for produced consumption goods. Both factors stimulate saving. Accordingly, the growth rate of consumption rises over time. Production benefits not only from more natural capital but also from investment in man-made assets. Hence, the growth rate of production gradually rises after its initial fall.

The sectoral allocation of the economy develops in a non-monotonic way. Initially economic activity is relocated away from the pollution-intensive private goods sector towards the less polluting environmental R&D sector. Furthermore, consumption of final goods increases. This causes private capital accumulation to fall sharply, while pollution-augmenting technological progress proceeds rapidly. As a consequence, the private to public capital ratio K/h falls rapidly in the early phases of the transition. The high rate at which environmentally friendly technologies are developed allows for a gradual shift of resources back to the pollution-intensive Y-sector. Hence, the initial expansion of the publicly subsidized sector is reversed. In the later phases of transition, however, this sector expands again at the cost of the Y-sector. Since saving gradually rises, investment becomes more important and the relative size of the consumption goods sector shrinks.

In the long run, positive productivity effects associated with more natural capital are sufficiently strong to offset the initial crowding-out effects. As a consequence, in the long run, the rate of return and the rate of growth exceed their initial level. This higher growth rate is sustained by permanent higher investments in the three assets (private capital K, knowledge capital h, and natural capital N). Since the public H-sector provides necessary investment goods, the long-run income share of the public sector exceeds its initial share.

This scenario serves as a benchmark scenario for each of the scenarios, with different initial conditions, presented in the next subsections.

5.4 *Environment as Consumption Good: Immaterial Benefits of Pollution Reduction*

In the second scenario, the long-run welfare gains are as high as in the benchmark scenario, but these gains stem entirely from amenity effects. Productivity effects of a clean environment are absent ($a = 0$, $\phi > 0$). In other words, the environment is a pure consumption good, *e.g.* because of the aesthetic value of an unspoiled landscape and the mental benefits from clean air, good health, *etc.* In this case, crowding our of production in favor of investment in environmental amenities harms long-run production and consumption growth. Hence, while immaterial aspects of welfare (the enjoyment of a cleaner environment, health, *etc.*) improve substantially, permanent income in terms of material consumption goods (produced commodities) falls sharply.

The short-run effects on production and material consumption growth are even more dramatic compared to the long-run effects and compared to the benchmark case (see Figure 4). Consumers anticipate the benefits from higher future environmental quality. In order to smooth their utility stream over time, they consume more final goods during the initial phases of the transition when environmental quality is still low.[17] This hurts saving, investment, and income growth in the short run. In contrast to the benchmark case, there are no offsetting increases in productivity due to a more productive natural capital stock. Thus, the fall in production growth is relatively large. As environmental quality rises over time, consumers substitute consumption of natural services for material consumption. Hence, investment in man-made assets and growth recover, but only partly. The entire path is characterized by a shift from investment goods towards consumption goods: in earlier periods towards material consumption goods, in later periods towards natural consumption goods (N). This shift causes growth do decline in both the short run and the long run.

The shift from investment goods towards relatively pollution-intensive consumption goods increases the importance of environmentally friendly technologies so that the long-run K/h ratio declines more than it does in the benchmark case. The same shift towards consumption goods accounts for the decline (as opposed to the benchmark rise) in the long-run share of the public sector, which provides investment goods (see Figure 4).

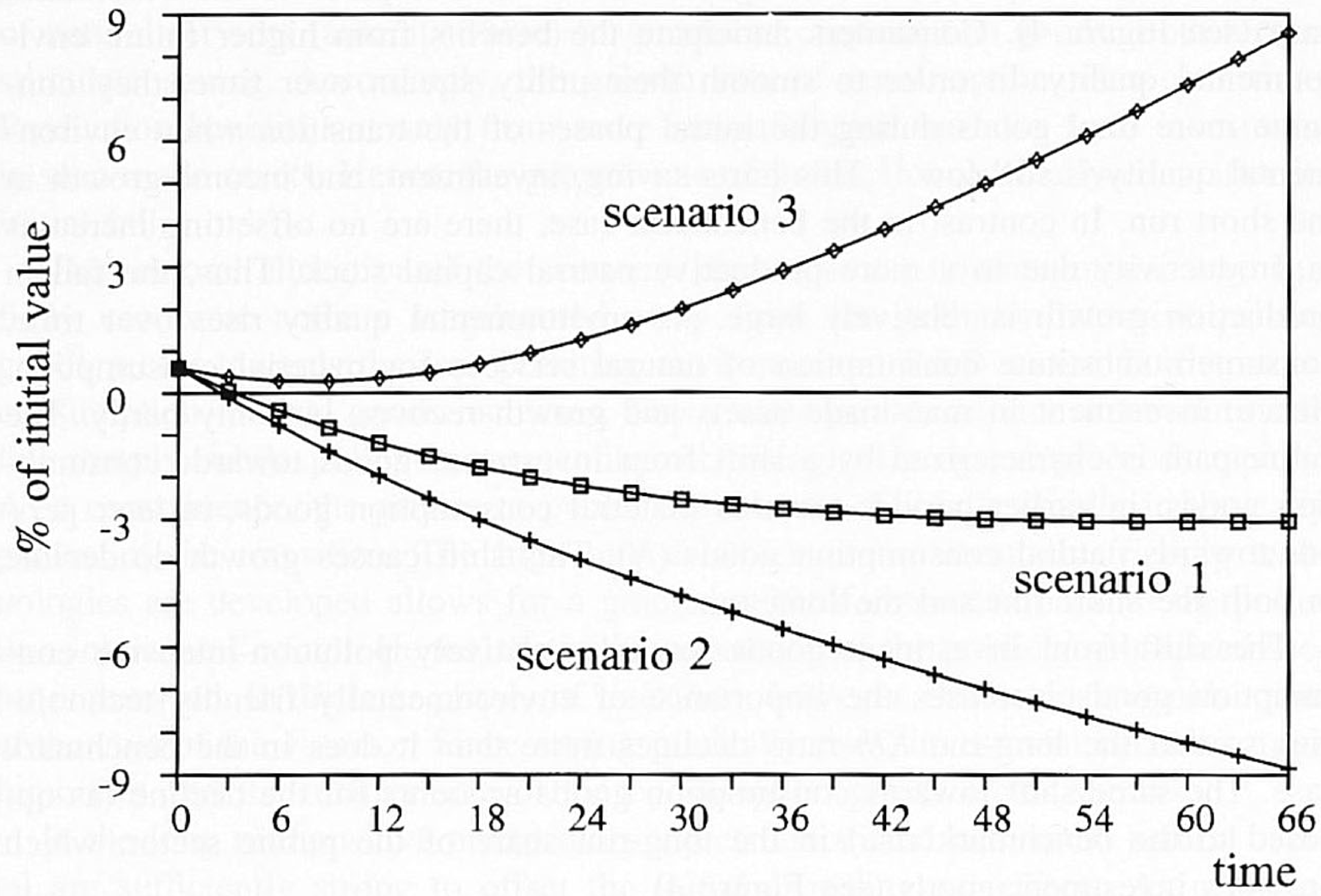
5.5 *Environment as Investment Good: Material Benefits of Pollution Reduction*

In the third scenario, the long-run welfare gains are again as high as in the benchmark scenario. However, in this scenario these gains stem entirely from productivity effects, *i.e.* the environment is a pure investment good ($\phi = 0$, $a > 0$), *e.g.* because low environmental quality increases depreciation and maintainance requirements of capital, adversely affects the health and productivity of workers, *etc.* In this case environmental policy implies a shift away from consumption towards investment. As a consequence, long-run productivity and growth rise (see Figure 4). In contrast to the benchmark scenario, even short-run growth rises, because rapidly accruing productivity gains, as a result of investment in natural capital, offset the crowding-out of investment in man-made assets. Permanent income in terms of produced consumption goods increases.

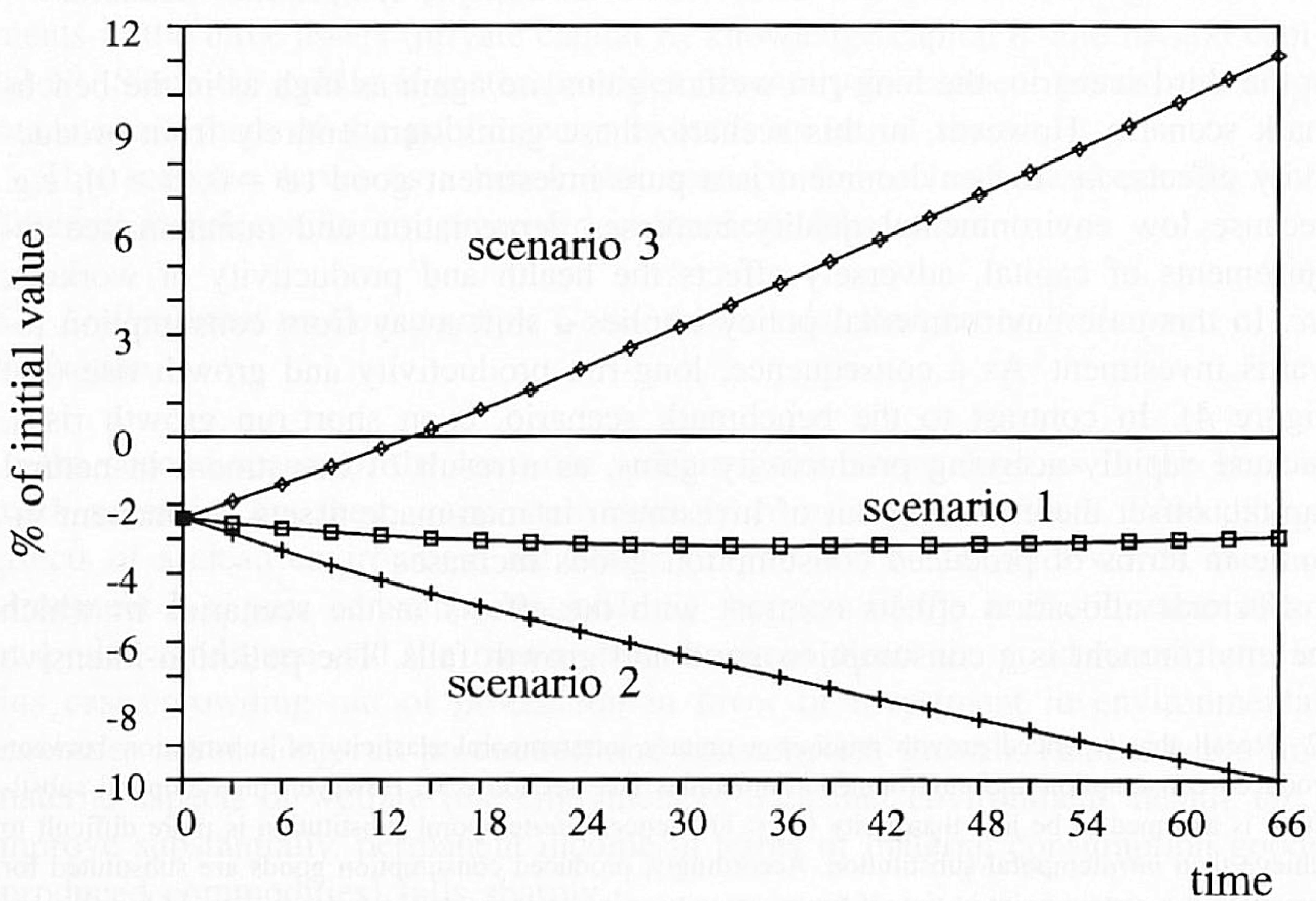
Sectoral allocation effects contrast with the effects in the scenarios in which the environment is a consumption good and growth falls. The pollution-intensive

17 Recall that balanced growth requires a unitary intratemporal elasticity of substitution between produced consumption and environmental amenities (see section 3.3). However, intertemporal substitution is assumed to be less than unity ($\sigma_c < 1$). Hence, *inter*temporal substitution is more difficult to achieve than *intra*temporal substitution. Accordingly, produced consumption goods are substituted for amenities at a certain point in time if future amenity gains are expected in order to prevent big changes in utility over time.

consumption $\tilde{c}$



production $\tilde{J}$



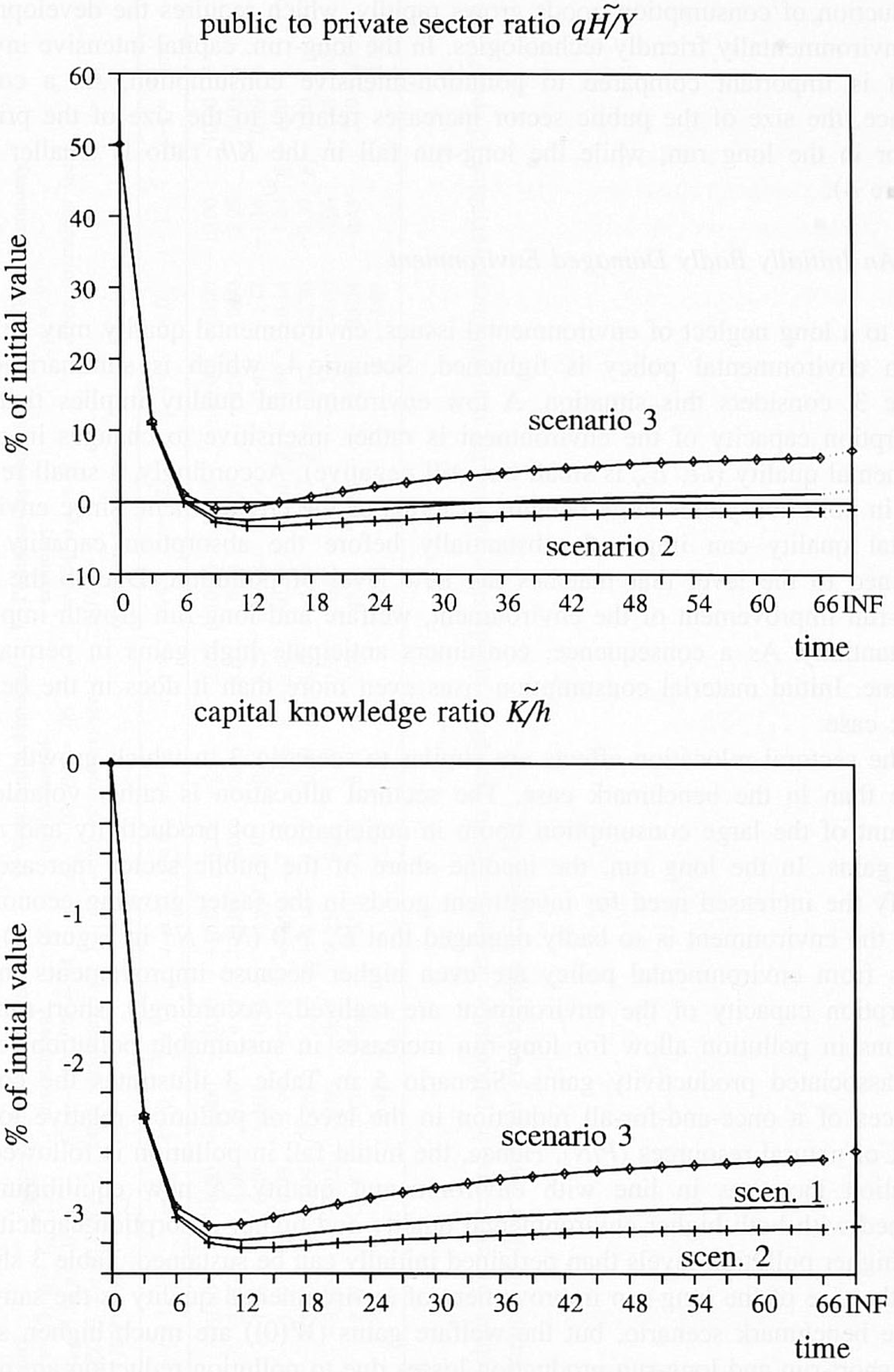


Figure 4 – The environment as a consumption good or as an investment good
scenario 1: benchmark ($a = 1/3$, $\phi = 1$)
scenario 2: the environment as a consumption good ($a = 0$, $\phi = 1.5$)
scenario 3: the environment as an investment good ($a = 1$, $\phi = 0$)
other parameters: see Table 3.

production of consumption goods grows rapidly, which requires the development of environmentally friendly technologies. In the long-run, capital-intensive investment is important compared to pollution-intensive consumption. As a consequence, the size of the public sector increases relative to the size of the private sector in the long run, while the long-run fall in the K/h ratio is smaller (see Figure 4).

5.6 *An Initially Badly Damaged Environment*

Due to a long neglect of environmental issues, environmental quality may be low when environmental policy is tightened. Scenario 4, which is summarized in Table 3, considers this situation. A low environmental quality implies that the absorption capacity of the environment is rather insensitive to changes in environmental quality (*i.e.* E_N is small but still negative). Accordingly, a small reduction in pollution yields large benefits in terms of the environment, since environmental quality can improve substantially before the absorption capacity has declined to the level that matches the new level of pollution. Due to the vast long-run improvement of the environment, welfare and long-run growth improve substantially. As a consequence, consumers anticipate high gains in permanent income. Initial material consumption rises even more than it does in the benchmark case.

The sectoral relocation effects are similar to scenario 3 in which growth rises more than in the benchmark case. The sectoral allocation is rather volatile on account of the large consumption boom in anticipation of productivity and amenity gains. In the long run, the income share of the public sector increases to satisfy the increased need for investment goods in the faster growing economy.

If the environment is so badly damaged that $E_N > 0$ ($N < N^E$ in Figure 1), the gains from environmental policy are even higher because improvements in the absorption capacity of the environment are realized. Accordingly, short-run reductons in pollution allow for long-run increases in sustainable pollution levels and associated productivity gains. Scenario 5 in Table 3 illustrates the consequences of a once-and-for-all reduction in the level of pollution relative to the stock of natural resources (P/N). Hence, the initial fall in pollution is followed by pollution increases in line with environmental quality. A new equilibrium is reached with both higher environmental quality and higher absorption capacity so that higher pollution levels than pertained initially can be sustained. Table 3 shows that the size of the long-run improvement of environmental quality is the same as in the benchmark scenario, but the welfare gains ($\tilde{W}(0)$) are much higher, since both short-run and long-run production losses due to pollution reduction are much lower. In the long run, polluting inputs are less scarce, which allows for a decline in the relative importance of environmentally friendly technologies (K/h increases as opposed to the fall in the benchmark scenario).

TABLE 3 – SCENARIOS WITH EXOGENOUS POLLUTION REDUCTION

	1. Benchmark $\vartheta = .03$; $\sigma_c = 2/3$; $\phi = 1$; $\omega = .238$; $\sigma_{KZ} = .8$; $a = 1/3$; $g = .02$; $Y_p P/Y = .25$; $H_p P/H = .1$ $E_N = -.04$; $P/N = .032$			**4. Badly damaged environment** $E_N = -.02$; $P/N = .04$ other parameters: see 1			**5. Very badly damaged environment** $E_N = .02$; $P/N = .06$ other parameters: see 1			**6. Pollution-dependent economy** $\omega = .364$; $\sigma_{KZ} = .5$; $Y_p P/Y = .6$ other parameters: see 1			**7. Flexible economy** $\sigma_c = .95$ other parameters: see 1			
time	$t = 0$	$t = 12$	$t \to \infty$	$t = 0$	$t = 12$	$t \to \infty$	$t = 0$	$t = 12$	$t \to \infty$	$t = 0$	$t = 12$	$t \to \infty$	$t = 0$	$t = 12$	$t \to \infty$	time
$\tilde{P}$	−10.00	−10.00	−10.00	−10.00	−10.00	−10.00	−5.33	−2.28	2.67	−10.00	−10.00	−10.00	−10.00	−10.00	−10.00	$\tilde{P}$
$\tilde{N}$	0.00	3.05	8.00	0.00	4.27	20.00	0.00	3.05	8.00	0.00	3.05	8.00	0.00	3.05	8.00	$\tilde{N}$
$\tilde{r}$	−2.17	−1.16	0.49	−2.17	−0.75	4.49	−1.02	0.61	3.25	−3.08	−2.06	−0.41	−2.17	−1.16	0.49	$\tilde{r}$
$\tilde{c}$	0.60	−1.19	$\tilde{g}_c = 0.99$	1.94	−0.18	$\tilde{g}_c = 8.99$	1.74	0.66	$\tilde{g}_c = 6.49$	−0.38	−2.61	$\tilde{g}_c = -0.82$	−0.14	−1.24	$\tilde{g}_c = 1.20$	$\tilde{c}$
$\tilde{J}$	−2.38	−2.90	$\tilde{g}_J = 0.99$	−2.38	−3.07	$\tilde{g}_J = 8.99$	−1.27	−0.60	$\tilde{g}_J = 6.49$	−3.64	−4.60	$\tilde{g}_J = -0.82$	−2.36	−2.39	$\tilde{g}_J = 1.20$	$\tilde{J}$
$K/\tilde{h}$	0.00	−3.18	−2.92	0.00	−3.33	−2.67	0.00	−1.29	0.98	0.00	−5.95	−5.71	0.00	−3.06	−2.88	$K/\tilde{h}$
$qH/\tilde{Y}$	50.11	−2.49	1.87	50.11	−5.01	6.01	34.11	−5.41	2.99	43.41	0.34	2.00	43.34	−0.43	2.10	$qH/\tilde{Y}$
$\tilde{W}(0)$	2.43			6.43			5.52			0.54			3.09			$\tilde{W}(0)$

Remarks:
All tilded variables are expressed as percentage deviations from the initial steady-state values; for non-stationary variables ($\tilde{c}$ and $\tilde{J}$), the percentage deviation of their long-run growth rate is given for $t \to \infty$.

5.7 *A Pollution/Energy Dependent Economy*

In scenario 6 production depends heavily on the use of polluting inputs. In particular, the production elasticity of (effective) pollution in the Y-sector is larger than it is in the benchmark case. Moreover, substitution possibilities between pollution and private capital are smaller. This scenario models an economy with a large agricultural sector, using pesticides responsible for acidification of the soil, or, alternatively, an economy with a large energy-intensive industrial sector.

The welfare gains are lower in scenario 6 than they are in the benchmark case because the costs of pollution reduction are high. The initial adverse impacts on the rate of return to man-made capital, the level of production and growth are large. The long-run growth rate falls: an economy with a pollution-dependent production structure faces a stronger trade-off between material consumption and environmental quality than an economy with a less pollution-dependent production structure.

Due to the lower intrasectoral substitution possibilities between pollution and private capital, the reduction in pollution provokes a larger intersectoral relocation towards the less pollution-intensive H-sector. Moreover, publicly provided technology capital (*i.e.* h) becomes relatively more important as a substitute for pollution. Hence, the public sector expands more than it does in the benchmark case.

5.8 *A Flexible Economy*

The consequences of a higher rate of intertemporal substitution are illustrated by scenario 7. Consumers are willing to accept larger fluctuations in their utility stream. Hence, they are more willing to postpone consumption and to substitute material consumption and environmental services intertemporally. This results in stronger growth effects of pollution reduction, both in the short as well as in the long run, because future rises in the rate of return invoke a larger savings reaction. Consumers even accept a decline in the initial level of consumption. The lower levels of consumption in the early phases of transition imply a less volatile sectoral relocation pattern, as private capital accumulation is relatively less affected. Welfare gains are higher because consumers discount future gains to a lesser extent.

6 OPTIMAL ENVIRONMENTAL POLICY

The previous section assumed that the flow of pollution (or, in scenario 5, the pollution to environmental quality ratio) is reduced exogenously to a permanently lower level. This is not necessarily an optimal policy. At each point in time the optimal path of pollution reduction trades off the benefits and costs of pollution reduction, which may vary over time. In particular, the level of pollution is optimal if the rate of return on environmental investment equals the rate of return on alternative investment (see (1.8)). This section studies optimal pollution reduction in the one-sector version of the model. To this end, the model in Table 1 is linearized. It includes optimality condition (1.8), which was left out in the previous section.[18] Moreover, the linearization takes place around an *optimal* balanced-growth path, so that the rate of return is the same on all assets ($r = r^N$) in the initial situation.

6.1 *Solving the One-sector model*

Although analytical results can be derived for more general cases, most points can be made by showing the results for the special case of a unitary elasticity of intertemporal substitution ($\sigma_c = 1$). In this case the one-sector model in Table 1 can be linearized and, subsequently, reduced to the following differential equations (see Smulders 1995b):

$$\dot{\tilde{N}} = E_N \tilde{N} - (P/N)\tilde{P} \tag{16}$$

$$\dot{\tilde{P}} = -\left(\frac{-E_{NN}N - aE_N + (\vartheta - E_N)\,[a - (1-\gamma)J_{NN}N/J_N + \gamma]}{(1-\omega)\,(2-\sigma_{KZ})}\right)\tilde{N} + \\ + (\vartheta - E_N)\tilde{P} + (\vartheta - E_N)\gamma\tilde{\phi} \tag{17}$$

where a variable with a tilde denotes the percentage deviation from the initial steady state and $\gamma \equiv \phi\vartheta/(\phi\vartheta + ar)$. Figure 5 depicts the phase diagram both for the case where $E_N > 0$ and the case where $E_N < 0$. The model is saddle-point stable.

6.2 *Environmental Policy to Attain the Social Optimum*

By increasing the amenity value of the environment from $t = 0$ onwards (*i.e.* $\tilde{\phi} > 0$), the initial balanced-growth path is no longer optimal. Hence, the economy is suddenly confronted with a situation that is similar to the starting point of all scenarios in section 4. Point O in Figure 5 represents this steady state. The figure shows that starting from low environmental quality, the optimal pollution level is *below* its long-run optimal level (see point B). Hence, pollution overshoots. It is optimal to reduce pollution drastically in initial phases and, subsequently, to gradually increase pollution to its long-run optimal level.

18 Of course the two-sector version with optimal pollution can be derived from Table 2 if the inequality sign in (2.13) is replaced by the equality sign.

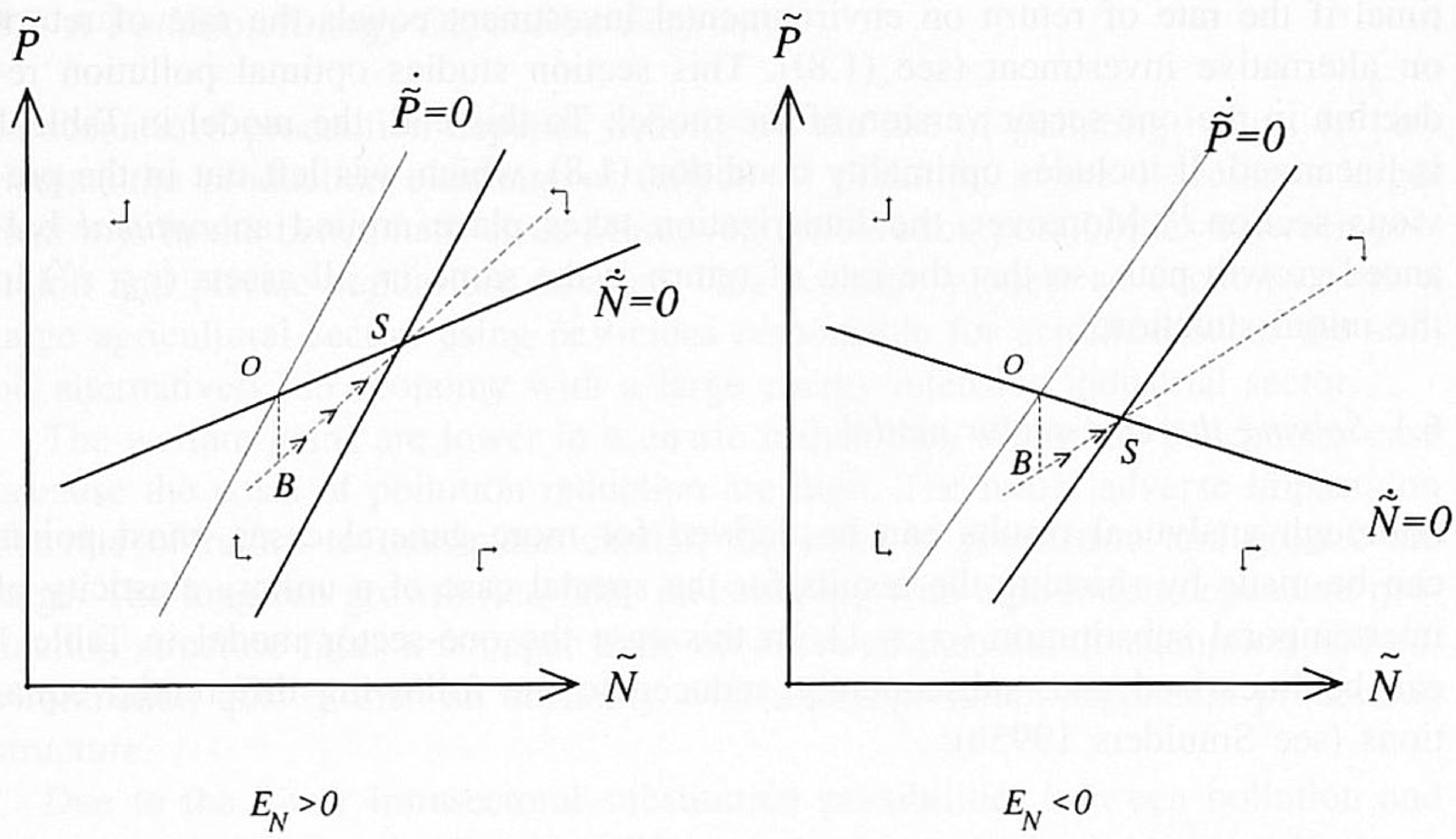


Figure 5 – Optimal environmental policy

The intuition is provided in Figure 2. As environmental quality falls below its optimal level, the returns to investment in environmental quality increase, that is, the costs of pollution reduction are lower. This follows from the role of environmental quality in ecology, production and utility. First, the effect of pollution reduction on environmental quality diminishes when environmental quality improves due to the entropy law. In particular, the higher environmental quality is, the more difficult it is to increase the absorption capacity of the environment ($E_{NN} < 0$). This increases the cost of pollution reduction, since absorption capacity determines the long-run sustainable level of pollution and productivity. Second, when environmental quality gradually improves, the productivity of man-made assets improves (if $a > 0$), which makes it costlier to forego production by maintaining low polluting-input levels. Finally, when N improves, produced consumption becomes scarce relative to environmental amenities (if $\phi > 0$), which makes production more attractive and pollution reducton costlier. In sum, it is optimal to reduce pollution when environmental quality is still low, since then the benefits of pollution reduction are largest.

7 CONCLUDING REMARKS

There is no *a priori* reason to exclude the possibility of unlimited economic expansion that preserves a stable environmental quality. While the physical environment is subject to limited creation and regeneration of natural resources, knowledge creation may be unlimited. Increases in knowledge may fuel economic growth without the need for increasing damage to the environment. This possibility was explored here in a dynamic general equilibrium model in which man-made assets (capital and knowledge) and natural assets (the environment) are endogenously accumulated. Within this model, the exact conditions for feasibility and optimality of ecologically sustainable growth were derived. The comparative statics and simulations restricted the model to situations of balanced sustainable growth. Environmental policy turned out to improve not only welfare but also, in many cases, the long-run growth performance of the economy, despite a short-run fall in production levels and investment in man-made assets. Although the model can be extended and refined in many directions (*e.g.* by considering population growth, introducing irreversibilities or disaggregating the environmental resource stock in exhaustible and renewable parts), this result is driven by the fairly general assumption that the environment provides necessary (rival and non-rival) inputs to economic production and accumulation processes. Hence improvements in environmental quality may boost the productivity of the environment and growth.

Many environmentalists (see Daly 1980) favor a stationary economy without growth (see also Jongeneel 1992). At first sight this seems to be in sharp contrast to the view expressed here and in many other endogenous growth models that incorporate environmental aspects, but a large part of the controversy on growth and the environment is due to different definitions of growth and income. Daly defines growth as 'quantitative increase in the scale of the physical dimensions of the economy; *i.e.* the rate of flow of matter and energy through the economy (...)' (Daly 1987, p. 36). In this terminology, the model in this paper features no long-term growth. The economic expansion fueled by increases in knowledge is then better labeled development. Daly agrees that 'there may or may not exist limits to development' (*ibidem*). One of the important messages from the controversy on growth and the environment is that the qualitative direction of economic expansion and the bias of technological progress are the real issue.

Furthermore, the endogenous growth perspective on environmental issues does not necessarily exclude a stationary state as a long-run equilibrium. By imposing non-decreasing returns with respect to the accumulation of man-made factors, endogenous growth theory argues that human creativity has to be strong enough to continuously overcome the limits of nature. If it becomes more and more difficult to find new ideas to derive more utility from the same flow of natural resources, the rate of sustainable growth tapers off and a stationary state arises in the long run. In this respect, the theory is optimistic. Knowledge not only concerns scientific principles and high-tech applications, but also social attitudes regarding how to cope with the environment and how to enjoy it. The inexhaustible and non-rival nature of knowledge and the contribution of social interaction, communication, and inspiration makes it less likely that limits to human creativity are binding. Another threat to unlimited economic expansion is the level of real returns to investment in new ideas. Although human creativity may be potentially an unlimited source for economic development, it may be optimal not to use it because the costs are too high. If the return to invention falls short of society's time preference ($r < \vartheta$, see (1.6)), the stationary state arises. Hence, high development costs for durable modes of energy and new environmentally friendly products in the absence of good substitutes may justify the plea for very low growth.

The main message from an endogenous growth perspective is perhaps the role of investment and policy. Both are essential in establishing sustainable growth. Continuous investment is needed to attain higher productivity (in terms of utility) per unit of natural resource input. Public investment has a large role to play if knowledge is non-rival and non-excludable. Moreover, public environmental policy should prevent over-exploitation of the environment and should take care of the internalization of the many-sided benefits of high environmental quality for economic and personal life.

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Summary

ENVIRONMENTAL POLICY AND SUSTAINABLE ECONOMIC GROWTH AN ENDOGENOUS GROWTH PERSPECTIVE

This paper investigates the consequences of environmental policy for welfare, consumption and production growth in a situation in which environmental quality is initially too low. The natural environment is incorporated in endogenous growth theory in a way that is consistent with some simple notions from the laws of thermodynamics. Environmental policy affects growth, both in the long run and in the short run, by affecting the productivity of investment and the savings behavior of consumers. The environment provides necessary inputs to economic production and accumulation processes. Hence improvements in environmental quality that follow environmental policy may boost the productivity of the environment and growth.